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# $\Delta\Gamma_{B_s}$ beyond the Standard Model

Ulrich Nierste  
Fermilab



## Outline

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2. New physics in  $\Delta\Gamma_{B_s}$
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## $B_s - \bar{B}_s$ mixing basics

Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} |B_s(t)\rangle \\ |\bar{B}_s(t)\rangle \end{pmatrix} = \left( M - i \frac{\Gamma}{2} \right) \begin{pmatrix} |B_s(t)\rangle \\ |\bar{B}_s(t)\rangle \end{pmatrix}$$

where  $B_s \sim \bar{b}s$  and  $\bar{B}_s \sim b\bar{s}$ .

3 physical quantities in  $B_s - \bar{B}_s$  mixing:

$$|M_{12}|, \quad |\Gamma_{12}|, \quad \phi = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right)$$

Two mass eigenstates:

Lighter eigenstate:  $|B_L\rangle = p|B_s\rangle + q|\bar{B}_s\rangle$ .

Heavier eigenstate:  $|B_H\rangle = p|B_s\rangle - q|\bar{B}_s\rangle$  with  $|p|^2 + |q|^2 = 1$ .

with masses  $M_{L,H}$  and widths  $\Gamma_{L,H}$ .

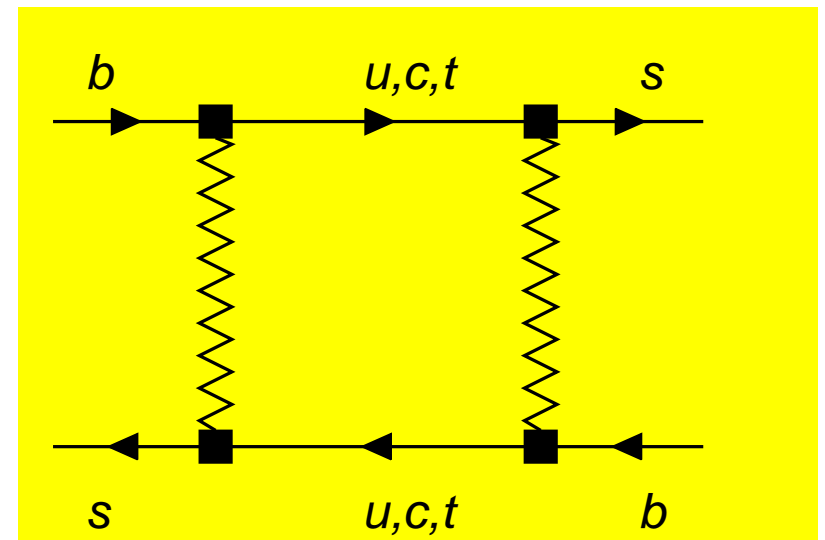
Relation of  $\Delta m$  and  $\Delta\Gamma$  to  $|M_{12}|$ ,  $|\Gamma_{12}|$  and  $\phi$ :

$$\Delta m = M_H - M_L \simeq 2|M_{12}|, \quad \Delta\Gamma = \Gamma_L - \Gamma_H \simeq 2|\Gamma_{12}| \cos \phi$$

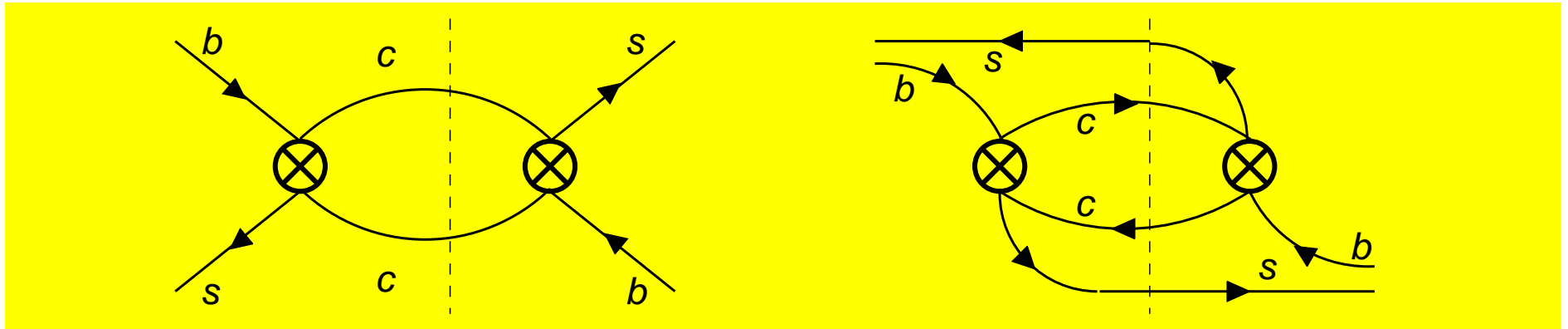
$M_{12}$  stems from the **dispersive** (real) part of the box diagram, internal  $(\bar{t}, t)$ .

$\Gamma_{12}$  stems from the **absorptive** (imaginary) part of the box diagram, internal  $(\bar{c}, c)$ .

( $u$ 's are negligible).



$\Gamma_{12}$  stems from final states common to  $B_s$  and  $\overline{B}_s$ .



Crosses: Effective  $|\Delta B| = 1$  operators from  $W$ -exchange.

$\Gamma_{12}$  is a CKM-favored tree-level effect associated with final states containing a  $(\overline{c}, c)$  pair.

## $\Delta\Gamma$ in the Standard Model

Standard Model:

CP-violating phase  $\phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$  negligibly small.

Identify mass eigenstates with CP eigenstates:

$$\begin{aligned} |B_L\rangle &= |B_s^{\text{CP-even}}\rangle = \frac{1}{\sqrt{2}} [|B_s\rangle - |\overline{B}_s\rangle] \\ |B_H\rangle &= |B_s^{\text{CP-odd}}\rangle = \frac{1}{\sqrt{2}} [|B_s\rangle + |\overline{B}_s\rangle] \end{aligned}$$

## Measurements

Time evolution of any decay of an  $\text{untagged } (\overline{B}_s \rightarrow f)$  decay:

$$\Gamma[f, t] \propto |\langle f | B_L \rangle|^2 e^{-\Gamma_L t} + |\langle f | B_H \rangle|^2 e^{-\Gamma_H t}$$

In the Standard Model the  $b \rightarrow \bar{c}cs$  decay amplitude has approximately the same CP phase as  $M_{12}$ . Consider  $f = (J/\psi\phi)_{L=0}$  (i.e. S-wave), which is CP-even:

$$\langle (J/\psi\phi)_{L=0} | B_H \rangle = \langle (J/\psi\phi)_{L=0} | B_s^{\text{CP-odd}} \rangle = 0$$

$\Rightarrow$  Lifetime measured in  $(\overline{B}_s \rightarrow (J/\psi\phi)_{L=0})$  determines  $\Gamma_L$ .

Next consider a decay which is flavor-specific, i.e.

$$\bar{B}_s \not\rightarrow f \text{ and } B_s \not\rightarrow \bar{f}.$$

Examples:  $B_s \rightarrow X \ell^+ \nu_\ell$  or  $B_s \rightarrow D_s^- \pi^+$ . Then  $|\langle f | B_L \rangle| = |\langle f | B_H \rangle|$  and

$$\Gamma[f, t] \propto e^{-\Gamma_L t} + e^{-\Gamma_H t}$$

$\Rightarrow$  Lifetime measured in  $(\bar{B}_s) \rightarrow (J/\psi\phi)_{L=0}$  determines a weighted average of  $\Gamma_L$  and  $\Gamma_H$ .

$\Rightarrow$  combine both measurements to find  $\Delta\Gamma$ .

Or use theory input:

$$\Gamma_{B_s} \equiv \frac{\Gamma_L + \Gamma_H}{2} = \Gamma_{B_d} + \mathcal{O}(1\%)$$

to determine  $\Delta\Gamma$  only from  $\Gamma_L$  measured in  $(\bar{B}_s) \rightarrow (J/\psi\phi)_{L=0}$  via

$$\Gamma_L - \Gamma_{B_s} = \frac{\Delta\Gamma}{2}$$

Or determine  $\Gamma_H$  from a lifetime measurement from decays to the CP-odd final state  $(J/\psi\phi)_{L=1}$  (i.e. P-wave) to find:

$$\Gamma_L - \Gamma_H = \Delta\Gamma$$

## 2. New physics in $\Delta\Gamma_{B_s}$

$\Gamma_{12}$  is a tree-level quantity and is difficult to change significantly in models of new physics. Assume first  $\Gamma_{12} = \Gamma_{12,\text{SM}}$ .

Then new physics can only enter  $\Delta\Gamma$  via  $\cos\phi$ . Two effects:

- $\Delta\Gamma = 2|\Gamma_{12}|\cos\phi = \Delta\Gamma_{\text{SM}}\cos\phi$ .
- $|B_L\rangle$  and  $|B_H\rangle$  are no more CP eigenstates.
  - $\Rightarrow$  both  $|B_L\rangle$  and  $|B_H\rangle$  can decay into  $(J/\psi\phi)_{L=0}$
  - $\Rightarrow$  the lifetime measured in  $\bar{B}_s \rightarrow (J/\psi\phi)_{L=0}$  is no more  $1/\Gamma_L$ .

Recall that for an **untagged**  $\bar{B}_s \rightarrow f$  decay:

$$\Gamma[f, t] \propto |\langle f | B_L \rangle|^2 e^{-\Gamma_L t} + |\langle f | B_H \rangle|^2 e^{-\Gamma_H t}$$

For a  $b \rightarrow c\bar{c}s$  decay into a **CP-even** final state  $f_{CP+}$  (like  $(J/\psi\phi)_{L=0}$ ):

$$|\langle f_{CP+} | B_L \rangle|^2 = \frac{1 + \cos \phi}{2} |\langle f_{CP+} | B_s^{\text{CP-even}} \rangle|^2$$

$$|\langle f_{CP+} | B_H \rangle|^2 = \frac{1 - \cos \phi}{2} |\langle f_{CP+} | B_s^{\text{CP-even}} \rangle|^2$$

while for the **CP-odd** final state  $f_{CP-}$ :

$$|\langle f_{CP-} | B_L \rangle|^2 = \frac{1 - \cos \phi}{2} |\langle f_{CP-} | B_s^{\text{CP-odd}} \rangle|^2$$

$$|\langle f_{CP-} | B_H \rangle|^2 = \frac{1 + \cos \phi}{2} |\langle f_{CP-} | B_s^{\text{CP-odd}} \rangle|^2$$

Thus seeing two exponentials in  $(\bar{B}_s) \rightarrow (J/\psi\phi)_{L=0}$  implies new physics. In practice this is very difficult.

A maximum likelihood fit of

$$\Gamma[f, t] = A e^{-\Gamma_L t} + B e^{-\Gamma_H t}$$

to a single exponential

$$e^{-\Gamma_f t}$$

converges to

$$\Gamma_f = \frac{A/\Gamma_L + B/\Gamma_H}{A/\Gamma_L^2 + B/\Gamma_H^2}$$

Hartkorn, Moser 1999; Dunietz, Fleischer, U.N. 2000

Expand to second order in  $\Delta\Gamma$ :

$$\Gamma_f = \Gamma + \frac{A - B}{A + B} \frac{\Delta\Gamma}{2} - \frac{2AB}{(A + B)^2} \frac{(\Delta\Gamma)^2}{\Gamma} + \mathcal{O}\left(\frac{(\Delta\Gamma)^3}{\Gamma^2}\right)$$

For a  $b \rightarrow c\bar{c}s$  decay  $(\bar{B}_s) \rightarrow f_{CP\pm}$  find

$$\frac{A - B}{A + B} = \pm \cos \phi$$

Hence the  $\Delta\Gamma$  measurement from  $(\bar{B}_s) \rightarrow (J/\psi\phi)_{L=0}$  really determines

$$\Delta\Gamma'_{CP} \equiv \Delta\Gamma \cos \phi = \Delta\Gamma_{SM} \cos^2 \phi$$

Grossman 1996, Dunietz, Fleischer, U.N. 2000

$\Rightarrow$  Using the theory prediction for  $\Delta\Gamma_{SM}$  the Tevatron measurements of  $\Delta\Gamma'_{CP}$  constrain the allowed range of  $|\cos \phi|$ .

Further the measurements yield no information on the sign of  $\Delta\Gamma$ .

So a tight upper bound on  $|\Delta\Gamma|$  can establish  $\phi \neq 0$  and establish new physics. Conversely if experimentally  $|\Delta\Gamma| > 0$  is established, models of new physics are constrained, because regions near  $\phi = \pi/2$  and  $\phi = -\pi/2$  will be excluded. In the generic MSSM this constrains the phases of flavor-changing elements of the squark mass matrices as a function of the gluino and squark masses.

In the Standard Model have

$$B_L = B_s^{\text{short-lived}} = B_s^{\text{CP-even}}$$

$$B_H = B_s^{\text{long-lived}} = B_s^{\text{CP-odd}}$$

In the presence of new physics the short-lived eigenstate has always a larger CP-even component than the long-lived eigenstate. However,

$$\begin{aligned} \text{for } \cos \phi > 0: \quad & B_L = B_s^{\text{short-lived}}, \quad \text{and} \quad B_H = B_s^{\text{long-lived}}, \\ \text{for } \cos \phi < 0: \quad & B_L = B_s^{\text{long-lived}}, \quad \text{and} \quad B_H = B_s^{\text{short-lived}}, \end{aligned}$$

Hence for  $(\overline{B}_s) \rightarrow (J/\psi\phi)_{L=0}$ :

$$\begin{aligned} \Gamma[f_{CP+}, t] &\propto \frac{1 + \cos \phi}{2} e^{-\Gamma_L t} + \frac{1 - \cos \phi}{2} e^{-\Gamma_H t} \\ &= \frac{1 + |\cos \phi|}{2} e^{-\Gamma_{\text{short}} t} + \frac{1 - |\cos \phi|}{2} e^{-\Gamma_{\text{long}} t} \end{aligned}$$

Again this show that no information on  $\text{sgn } \cos \phi = \text{sgn } \Delta\Gamma$  is gained.

### 3. Lifetime measurements in $b \rightarrow s\bar{s}s$ decays

A combined fit to CP asymmetries in rare hadronic  $b \rightarrow s\bar{q}q$  decays measured at BaBar and BELLE indicates a deviation from the Standard Model by  $3.8\sigma$  (O. Tajima, Aspen 2005).

Consider a new CP phase  $\sigma$  in the  $b \rightarrow s\bar{s}s$  decay. Let now  $\bar{B}_s \rightarrow f_{CP+}$  denote a  $b \rightarrow s\bar{s}s$  decay into a CP-even final state, e.g.  $f_{CP+} = (\phi\phi)_{L=0}$ . With

$$\langle f_{CP+} | B_s \rangle \propto e^{i\sigma} \quad \text{and} \quad \langle f_{CP+} | \bar{B}_s \rangle \propto -e^{-i\sigma}$$

the coefficients in

$$\Gamma[f, t] \propto |\langle f | B_L \rangle|^2 e^{-\Gamma_L t} + |\langle f | B_H \rangle|^2 e^{-\Gamma_H t}$$

read:

$$|\langle f_{CP+} | B_L \rangle|^2 \propto \frac{1 + \cos(\phi + 2\sigma)}{2}, \quad |\langle f_{CP+} | B_H \rangle|^2 \propto \frac{1 - \cos(\phi + 2\sigma)}{2}$$

$$\Gamma[f_{CP+}, t] \propto \frac{1 + \cos(\phi + 2\sigma)}{2} e^{-\Gamma_L t} + \frac{1 - \cos(\phi + 2\sigma)}{2} e^{-\Gamma_H t}$$

For the **Standard Model** case  $\phi = \sigma = 0$  only  $B_L$  can decay into  $f_{CP+}$  and the lifetime measured in e.g.  $(\bar{B}_s) \rightarrow (\phi\phi)_{L=0}$  determines  $\Gamma_L$ .

If the lifetime measured in  $(\bar{B}_s) \rightarrow (\phi\phi)_{L=0}$  is **longer** than the one measured in  $(\bar{B}_s) \rightarrow (J/\psi\phi)_{L=0}$ , new physics in the  $b \rightarrow s\bar{s}s$  decay amplitude is established through  $\sigma \neq 0$ , with the possibility of  $\phi = 0$  or  $\phi \neq 0$ .

If the lifetime measured in  $(\bar{B}_s) \rightarrow (\phi\phi)_{L=0}$  is **shorter** than the one measured in  $(\bar{B}_s) \rightarrow (J/\psi\phi)_{L=0}$ , new physics in **both** the  $b \rightarrow s\bar{s}s$  decay amplitude and  $B_s - \bar{B}_s$  **mixing** is established through  $\sigma \neq 0$  and  $\phi \neq 0$ .

The same argument applies to the  $b \rightarrow s\bar{u}u$  amplitude triggering  $(\bar{B}_s) \rightarrow K^+ K^-$  except that here a small tree amplitude is present, so that  $\sigma \neq 0$  already in the **Standard Model**.

## 4. How to measure $\text{sgn } \Delta\Gamma_{B_s}$

The Tevatron analysis of  $(\overline{B}_s) \rightarrow J/\psi\phi$  determines

$$\Delta\Gamma'_{\text{CP}} \equiv \Delta\Gamma \cos\phi = \Delta\Gamma_{\text{SM}} \cos^2\phi.$$

This can, in principle, determine  $|\cos\phi|$  leaving  $\phi$  with a **four-fold** ambiguity in  $\phi$ . A measurement of the **semi-leptonic CP asymmetry** in  $B_s$  decays can determine  **$\sin\phi$** , leaving a **two-fold** ambiguity. Hence for an unambiguous determination of  $\phi$  we need  **$\text{sgn } \cos\phi$** .

An important subclass of models of new physics are scenarios with **minimal flavor violation**. In these models one has only two possibilities:  **$\cos\phi = +1$**  or  **$\cos\phi = -1$** , corresponding to  **$\Delta\Gamma > 0$**  and  **$\Delta\Gamma < 0$** .

Information on  $\text{sgn } \Delta\Gamma$  can be obtained from an angular analysis of the tagged decay  $B_s \rightarrow J/\psi\phi$ . This analysis involves time-dependent linear polarization amplitudes  $A_0(t)$ ,  $A_{||}(t)$  and  $A_{\perp}(t)$ . The angular distributions of the tagged decay involves

$$\text{Im} [A_0^*(t)A_{\perp}(t)] \quad (1)$$

which contains a term

$$- \cos \delta_2 \cos \phi \sin(\Delta mt)$$

where

$$\delta_2 = \arg [A_0(0)^* A_{\perp}(0)]$$

is a strong phase. Dighe, Dunietz, Fleischer 1998; Dunietz, Fleischer, U.N. 2000

Now  $\cos \delta_2$  can be determined through  $SU(3)_F$  symmetry from  $B_d \rightarrow J/\psi K^* [\rightarrow \pi^0 K_S]$ . While  $SU(3)_F$  is not exact, it is sufficient to determine  $\text{sgn } \cos \delta_2$ .

$\Rightarrow \text{sgn } \Delta\Gamma$  can be found.

## 5. Summary

- The lifetime analysis in  $(\overline{B}_s) \rightarrow J/\psi\phi$  determines  $|\Delta\Gamma| |\cos\phi| = \Delta\Gamma_{\text{SM}} \cos^2\phi$ . New physics can only diminish  $\Delta\Gamma$ . Experimentally excluding  $\Delta\Gamma = 0$  constrains the parameter space of e.g. supersymmetric models.
- Models of new physics with **minimal flavor violation** only allow  $\cos\phi = \pm 1$ . Determining  $\text{sgn}\Delta\Gamma = \text{sgn}\cos\phi$  can be achieved from an angular analysis of the **tagged** decay  $B_s \rightarrow J/\psi\phi$  in conjunction with  $B_d \rightarrow J/\psi K^* [\rightarrow \pi^0 K_S]$ .
- Lifetime measurements in  $(\overline{B}_s) \rightarrow \phi\phi$  or  $(\overline{B}_s) \rightarrow K^+ K^-$  can reveal a new CP-violating phase in  $b \rightarrow s\bar{s}s$  or  $b \rightarrow s\bar{u}u$  decays.